

DEVELOPMENT OF THE ULTRASONIC METHOD FOR MEASUREMENT OF FLUID FLOW

by

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INTRODUCTION

Although there are a number of basically different methods available for measuring the flow of fluids, there are situations in which, for one reason or another, the choice may be limited to a very few. One field of application where only a few methods are available is the measurement of large quantities of water, and the required precision, costs and the physical dimensions of the flow passages often preclude the use of these few.

A specific problem, that of measuring hydraulic turbine discharge, provided the incentive for the development of the ultrasonic method of flow measurement. Low-head developments in particular are difficult to measure because the water passages are usually short in length and the geometries of the intakes are unsuitable for existing methods. The means for obtaining performance data on these developments, particularly in the United States, is to step up laboratory tests on homologous models by utilizing formulas derived from basic dimensional relationships plus experience and empirical coefficients to compensate for other less tangible factors that vary with the size ratio. Index tests using combinations of piezometers in the turbine intake have been very helpful in extending performance data over a wide range of head conditions after the index has been proven reliable and its calibration determined from a direct method of field testing. Experience with the use of the scale formulas and index methods have convinced the authors that these methods alone do not provide sufficiently accurate information to realize maximum economies in operations.

When precise performance data are available, economies are obtained from preferential operation of the more efficient units and loading of machines in accordance with their incremental efficiencies. These methods of operation may be applied to a single multiple unit station, an inter-connection of several hydro stations, or a system of combined hydro and steam generating stations.

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With units of identical design, variations in performance between individual turbines may seem insignificant; however, field testing of a station with seven 42,500 hp. machines has shown differences of as much as 2 percent in efficiency. The tests in this case were made by the two-type current meter method using propeller type current meters with different pitch of vanes. The test results were very consistent and duplication tests on the same turbine showed a deviation band of less than 0.5 percent.

The scale formula method has been found considerably in error at the higher load points where cavitation begins to influence the performance. Model efficiency tests are usually made in the laboratory at sigma values higher than those existing in prototype operation; therefore step up of the model data do not reflect the effects of cavitation. Incremental operating efficiencies based upon performance from the model therefore can be very misleading.

The plant for which the ultrasonic method was originally intended is not suitable for current meters or any existing method of large flow measurement. The turbines have short and steep intakes and unguided approaches upstream from the head gate section. Volumes of flow exceed 3,000 cubic feet per second and it was not deemed practical to introduce any mechanical structure in these intakes because of the difficulties that would be encountered due to the obstruction of flow and because of the high cost of such an installation.

PRACTICAL CONSIDERATIONS

After establishing the need for a simple and accurate means for measuring large volumes of flow a theoretical study was made of all the known physical laws which might conceivably be used toward this end. In order for any approach to be worth the undertaking, it had to pass the test of two rigorous criteria:

1. Be absolute in method. That is, be capable of use without calibration by any other means or method, yet subject to easy comparison with known standards of the highest order of accuracy.
2. Be capable of measuring by volume, weight or velocity averaged over a prescribed area.

Several methods seemed to offer practical solutions to the above conditions but the use of ultrasound transmission seemed most adaptable to the measurement of large volumes of flow. None of the available literature on ultrasonics made any mention of the measurement of fluid velocity although interferometers for the measurement of absolute velocities of propagation were discussed

in detail. Unfortunately, none of these devices could be used to measure flow: Both mechanical and optical interferometers, however, contained the basic requirements of high sensitivity so inherently a part of the new method.

The prerequisite of a high degree of sensitivity arises from the small change in velocity being measured. In water the absolute propagation velocity is approximately 4800 feet per second. In order to measure flow at 1 foot per second to within 1 percent it thus becomes necessary to indicate changes in the absolute propagation velocity on the order of 1 part in 480,000. An interferometer is capable of doing this but only under strict laboratory conditions and with special regard to the maintenance of constant temperatures of both the fluid and the measuring apparatus.

Resolved in practical terms this meant that the mechanical parts of the interferometer must remain constant in spacing to within 2 micro-inches per foot of acoustic path.

It was later discovered that maintenance of constant temperature on the part of both fluid and mechanical apparatus had been considered by workers who had previously been granted patents [1-5] but in no other wise published their findings. In spite of their excellent efforts, the problem of constant transducer (converters of electrical to mechanical or mechanical to electrical energy) spacing remained as great as ever although they achieved a measure of success in reducing the effects of changing propagation velocities with variations in temperature of the fluid. Most of these researchers used three or more transducers to obtain these results.

By utilizing a reversal of transmission between two transducers it was found that errors introduced into the measurement by changes in spacing due to any cause could be kept proportional; i.e. a change in the acoustic path length of 1 percent would produce only a 1 percent error in the flow determinations.

The method as presently used thus measures the differences in the velocities of propagation of compression waves with and against the direction of flow between two reversible transducers as a measure of the velocity of flow [6]. Using these means it is necessary to know the absolute propagation velocity of sound in the fluid. A more basic method utilizing absolute transit times has been derived [7] whereby the propagation velocity in the liquid need not be known.

$$v = \frac{d/t_d - d/t_u}{2} = \frac{d}{2} \left(\frac{1}{t_d} - \frac{1}{t_u} \right)$$

Where v = velocity of flow

d = length of measuring section

t_d = absolute transit time for a compression wave to travel in the downstream direction the length of the measuring section

t_u = absolute transit time for a compression wave to travel in the upstream direction the length of the measuring section

It is believed that further development of the electronic and physical equipment will make the use of the above formula practical. When this is accomplished, the method should find a much wider field of application since it would provide a true measure of velocity regardless of the nature of the fluid.

The second criteria of area measurement has been overcome to a practical degree in the application of the method to rectangular water passages.

TESTS IN ONE-FOOT-DIAMETER PIPE

Many tests were conducted while the equipment went through various stages of development and have shown that the effects of turbulence, sedimentation, variations in temperature and changing contours of flow have but small effects on the accuracy of the method [8].

In the first application of the method an attempt was made to measure flow in a round or cylindrical section. The transducers

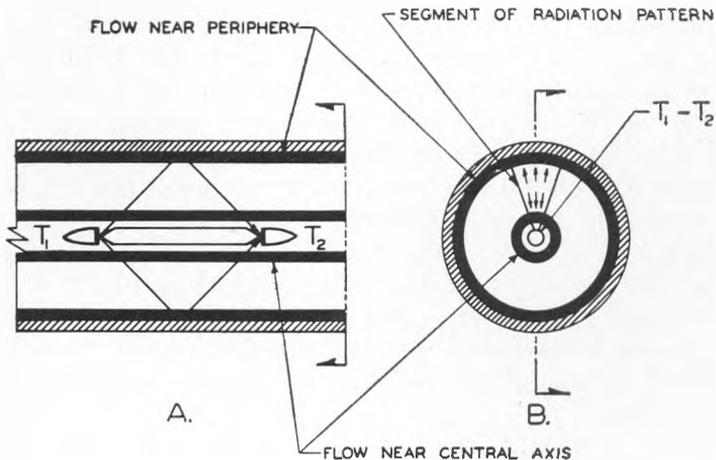


FIG. 1. MEASUREMENTS IN ROUND PIPE

- a — Axial Location Transducers $T_1 - T_2$
 b — Rod Pattern and Asymmetrical Flow

were mounted on a streamline form on the central axis of the pipe. Ultrasonic energy radiated from the one transducer out to the wall in the form of a cone and reflected to converge on the other transducer. A line diagram of this installation is shown in Fig. 1a.

While this system proved the basic concept, the precision was poor when compared to a carefully calibrated venturi. Figure 1b is an axial view of the round pipe in which the two darker bands represent water flowing at the same velocity; a small volume of flow near the center but a larger volume of flow at the periphery. The lines and arrows depict the radiation area of a small segment of the transducer as it radiates waves to the wall that converge again on the other transducer. It can be seen that the effect on the radiated energy would be alike for both the inner and outer bands of flow since the segment of radiated energy is narrow when passing through the inner flow and broad through the outer flow ring. Without knowing the true flow contour an accurate measure of the average velocity over the area of the pipe becomes impossible with this radiation pattern.

A photograph of this, the first attempt to use the new method, is shown in Fig. 2. This photograph is also interesting because it shows, in the foreground, an electronic variable frequency meter. The instrument was used to measure the differences in frequency when transmitting with and against the flow while maintaining a constant total number of wavelengths between transducers. Imagine, for example, that the transmission downstream is made at a frequency which at any instant produced 100 waves or wavelengths between the transducer transmitting and that receiving. Since the velocity of propagation is higher with than against the flow a reversal of the direction of transmission in an upstream direction makes necessary a change in the frequency of the power source to a lower frequency to maintain the required 100 wavelengths between transducers. The difference in these two frequencies of transmission can be inserted in a variation of the basic formula to provide an answer in terms of the velocity of flow. The frequency meter reads in cycles per second and serves to establish a time standard of high accuracy which can be further extended by calibration against the National Bureau of Standards Station WWV. Because flow velocities are always related to time the connection is obvious.

Many other techniques for utilizing reverse transmission between two transducers as a measure of flow are possible, but regardless of the means employed, one must use a direct or indirect

measure of the absolute transit times or difference in transit times as the indication of velocity.

APPLICATION TO RECTANGULAR WATER-PASSAGES

Because the most immediate problem for practical solution was the measurement of large volume flows in the rectangular intakes of low-head hydroelectric turbines a study was made to determine the method's ability to cope with this situation. A two-dimensional treatment of a rectangular water passage is shown in Fig. 3. The points T_1 and T_2 represent transducers and the circles drawn about T_1 the ultrasonic waves being radiated in the duct. By locating transducers on opposite walls displaced a known projected distance on the principal axis the connecting line of radiated energy becomes that shown by the dashed line. A mathematical treatment [7] assuming uniform flow proves that the effect on the transit time is

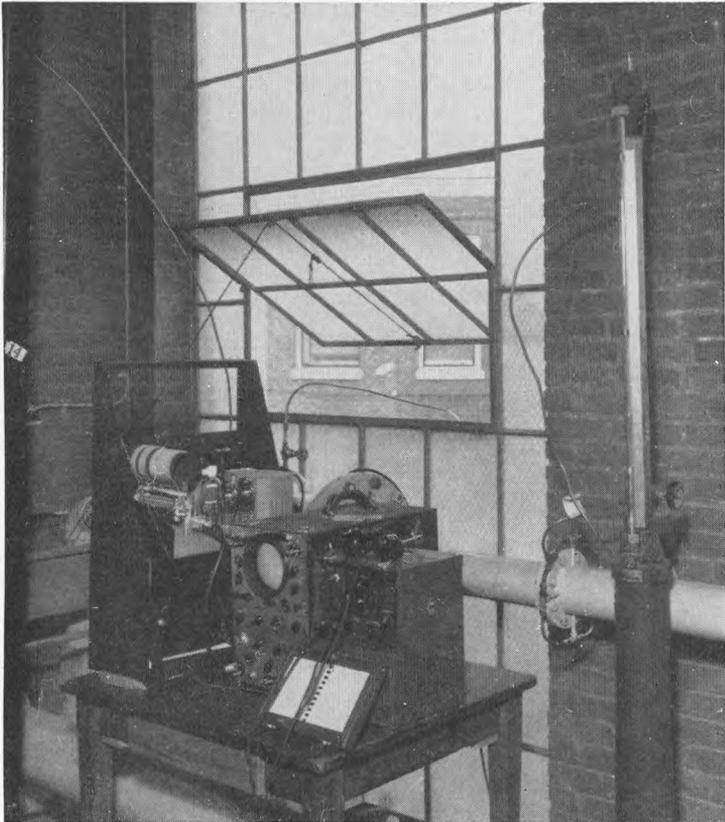


FIG. 2. FIRST TEST ASSEMBLY IN 12-INCH DIAMETER PIPE

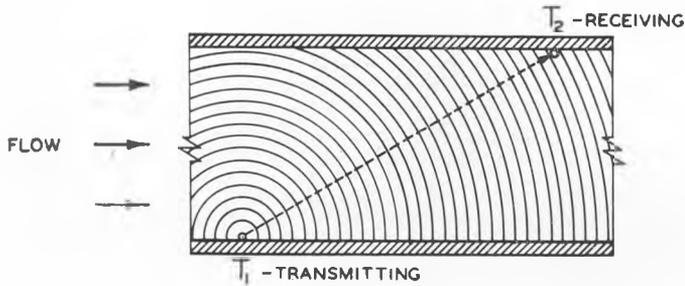


FIG. 3. MEASUREMENT AT ANGLE TO FLOW AXIS

the same for this condition as that when the transducers are displaced the same amount directly on the flow axis.

In crossing the duct at an angle further analysis indicates that for flow contours commonly encountered the total transit time will be affected by the average of the velocities along the path. Slight refraction errors are possible for highly distorted flows. These have been investigated and are reported on in detail in reference [7]. The maximum distortion where velocities ranged from 7 to 11 feet per second produced errors of about 2 percent. The negative or positive quantity of these errors were dependent on the physical orientation of the distortion relative to the plane of intersection of the area measurement.

MEASUREMENT OVER AN AREA

Figure 4 is a three-dimensional sketch of a rectangular duct and a block diagram of the electronic equipment used for the laboratory and full-scale tests. It will be noted that the transducers are tilted and displaced on the flow axis. The tilt was utilized as a means of overcoming undesired radiation paths which coupled the two transducers by reflecting from the top and bottom walls of the duct. The reflections would be objectionable in the average concrete intake because of dimensional errors in the geometry of the section and because the wavelength employed can be short enough for these walls to appear as very rough mirrors for reflecting ultrasound.

It will be further noted in Fig. 4 that the recorder compares the phase angle of the exciting voltage at the transmitting transducer with that from the transducer receiving the ultrasound via the water path. The direction of transmission was reversed at 5-second intervals by means of the interchanging switch. The difference in the two recorded phase angles was used as the measure of flow velocity.

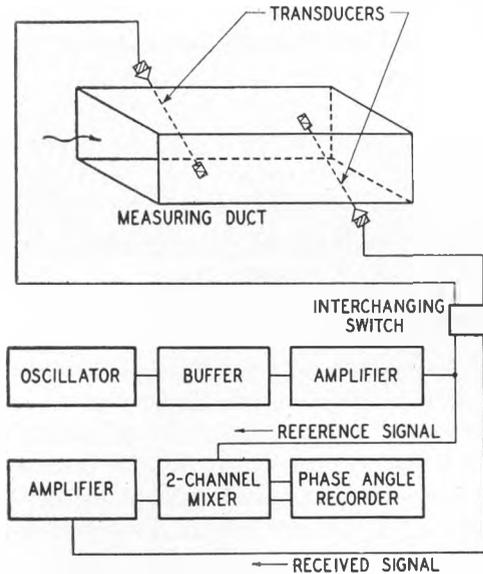


FIG. 4. BLOCK DIAGRAM OF EQUIPMENT USED

In order to radiate in even amounts over an area the transducers were designed as physical counterparts of electromagnetic antennae [9]. When they are mounted on opposing walls of the duct as shown in Fig. 4 the area between them becomes the thin invisible curtain affected by the velocities of flow. The transducer rod transmitting can be considered as an infinite number of point source radiators with an infinite number of receiving counterparts on the other transducer rod. A line connecting any one of the point sources with its receiving counterpart is lengthened or shortened an amount which is an average of the velocities encountered. If no flow exists, all transmission paths reach the true transducing element, a crystal in this case, simultaneously.

The crystal mentioned is only one of several transducing means which can be employed as driving and sensing elements. Compression waves in the long rods are created or sensed by these transducers in reciprocal fashion.

A sketch showing the solution to another problem is shown in Fig. 5. This problem resulted from the fact that no material of which the rods might be made is lossless to the passage of ultrasound. This results in a falling off of the intensity of the ultrasonic waves as they proceed down the rod and away from the crystal transducers. To align two such transducer rods in a parallel fashion and with the crystal drivers on the same ends would thus result

in a very non-uniform distribution of ultrasonic energy over the area between the rods. Figure 5 therefore shows the crystal drivers and rods aligned in an opposed fashion with the energy paths a, b and c all traversing an equal length water path and an equal total length of rod. This opposed mounting provides an even distribution of ultrasonic energy over the complete area between the rods and no errors can possibly occur from this source.

Figure 5 likewise serves to illustrate another point which is a test of the measure of parallelism of the transducer rods. This measurement is accomplished by observing the power output of the receiving transducer as the water in the passage is slowly raised or lowered. If the area is uniformly and adequately covered, the incremental changes in power output with the height of the water will be uniform. An uneven change in received signal would be an indication of a faulty installation. The amount of non-parallelism that can be tolerated depends upon the frequency used to obtain a minimum required degree of sensitivity and accuracy. This somewhat limiting condition can be reduced to a negligible degree by correlating the area and maximum flow velocities with the design of the electronic equipment.

With respect to area measurements another interesting phenomenon has been observed which it should be possible to use to advantage. This is the change in the power level of the received signal with distorted or turbulent flow. Very little was known on this subject when the testing was first started, and even to date no quantitative data have been recorded. The remarkable fact is that

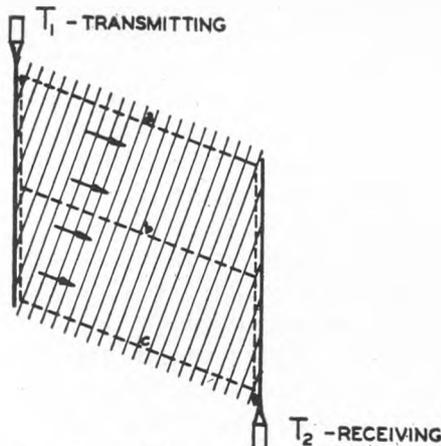


FIG. 5. EQUAL ENERGY DISTRIBUTION OVER AREA
a, b, c — EQUAL ENERGY PATHS

extreme turbulence seemed to have less of an effect on the power level of the transmitted signal than highly distorted flow although even the latter reduced the output by only a very few percent. With precisely controlled conditions it should be possible to establish some sort of a distortion index which would be indicative of the degree of distortion encountered by the ultrasonic waves. It would not, however, be possible to establish the shape of the contour using such data but rather its relation in degree to known flow contours.

ELECTRONIC EQUIPMENT

The electronic equipment has very little in its design that is unusual. The main consideration is the complete isolation of the reference and receiving transducer channels [10]. Any cross coupling between these links can produce erroneous results. These errors would not be apparent even with zero flow velocity, therefore each channel should be appraised separately for pick-up from the other.

It is possible to substitute lightly coupled dummy loads for the transducers and thus establish the correct functioning of the equipment in a zero flow condition. The frequency of operation can be easily checked against a frequency standard or the previously mentioned radio station WWV.

POTENTIAL USES

A photograph of the first large scale application is included as Fig. 6. The intake shown is the middle bay of three which comprise the intakes to a 42,500 horsepower adjustable blade-type turbine at the Safe Harbor Water Power Corp. plant, Conestoga, R. D. #2, Pa. The transducer can be seen as a thin line on the wall facing one of the authors. It was operated at 25 kilocycles, and flows in this single bay reached values of 3,000 cubic feet per second.

At one time experimental transducers were installed in a flume for testing the method's ability to measure in an open channel. A drought at the most inappropriate time prevented any save static or no-flow tests from being made, but all indications justified the belief that the results would have been the equal of those in the closed systems. Several techniques are available and have been used to evaluate accurately the correctness of the closed system installations. These same techniques were used to check the open flume installation mentioned above.

Dr. Julia Herrick of the Mayo Clinic is working with the method



FIG. 6. 30 FOOT TRANSDUCER INSTALLED IN 42,500-HORSEPOWER TURBINE INTAKE

in its adaptation to the measurement of blood flow where total flows of fractions of a cubic centimeter per second are being investigated.

Dr. F. H. Middleton and Wen-Hsiung Li of Johns Hopkins University's Institute for Cooperative Research have completed the development of an estuarine current meter using the method. This meter was designed to measure from 0.08 fps to 5.1 fps, a velocity ratio of 1 to 64. This instrument is remarkable in that only 9 electronic tubes are used and the flow readings over a long period of time are automatically recorded on film for later processing.

It is also understood that one large company is investigating the method's adaptation to the measurement of highly viscous flow where no other method has ever been completely successful.

In applying the method to gaseous flow there will probably be many new problems to overcome, the most significant anticipated being that of changes in the speed of propagation with changes in the intensity level of the ultrasound.

A demonstration flowmeter of the utmost simplicity has been shown [11] which measures air flow using two quite ordinary loud-speakers as transducers.

ACKNOWLEDGMENTS

The authors would like to acknowledge the very important assistance in the development and testing of this new method so freely given by Dr. S. K. Waldorf, Engineer of Research for Pennsylvania Water and Power Company, Lancaster, Pennsylvania.

DISCUSSION

Mr. Barron of the U. S. Geological Survey emphasized their urgent need for instruments to measure discharges in rivers where the usual stage-discharge relationships become grossly inaccurate, such as flat-sloped streams and those where backwater affects the surface slopes independently of the discharge. As an example he cited their problems on the Ohio, where the fall is sometimes only a few tenths of a foot between stations 20 miles apart, and errors in its determination may easily amount to as much as 20%. Discharges below about 20,000 cfs must be estimated under these conditions at most Ohio River Gaging Stations. The problem is complicated still more by unsteady conditions, in which case a calibration of the slope reach will be very complicated, costly, and possibly unattainable by the usual methods.

Because most attempts to record stream velocities continuously have proved impractical to date, they are intensely interested in the ultrasonic method. From their discussions with Mr. Swengel and others, they are quite hopeful that this measuring technique can be successfully applied in natural stream channels. Their present plans are to measure the mean velocity on a line between transducers placed on opposite banks of the river, rather than integrate across the entire cross-section. Their successful use of observations at a single point in determining total discharge gives them confidence in this possibility, since a line-velocity measurement across the main portion of the flowing water would be an even better parameter of the flow.

The immediate goal of the Geological Survey is to write a practical and workable set of specifications leading to a contract

for the development of ultrasonic velocity-measuring equipment. To do this, they need more definite information concerning the following characteristics of the ultrasonic method: Maximum range of transmission, maximum width-depth ratio attainable, range of velocities, practical accuracy over entire range of velocity, long-term stability, and amount of maintenance required.

When an instrument becomes available, the first installation may be made in the lower Sacramento River because of the urgent need for information to be used in their program to prevent salt-water intrusion. If this test installation is successful, then other applications would be numerous.

Mr. Tinney inquired about the cost of a unit, because this would be an important factor for a small laboratory. Mr. Swengel's reply was that theirs cost several thousand dollars, but was purely an experimental unit. The work at Johns Hopkins indicates that many simplifications could probably be made, but he would rather not guess at the eventual cost.

Mr. Mitchell asked about applications using hydraulic fluids or very small-scale installations. Mr. Swengel knew of one company which was now working with highly viscous fluids, and of Dr. Herrick's work at the Mayo Clinic measuring blood flow at velocities as low as a fraction of a centimeter per second. From the range of these studies, it appears that there is not much of a limit to either the scale of the systems which can be studied or the velocity range.

Mr. Strasberg wanted to know whether the flow must be uniform in the direction parallel to the rods. The speaker replied that the maximum errors occurred when this flow was non-uniform, but that in rivers the various errors cancelled each other within one-half of one percent.

In response to Mr. Shoumatoff's question concerning the effect of turbulence, the speaker stated that no real error was ever ascribed to turbulence as such, and that its only effect was to lower the signal slightly.

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